

# TWO-PHASE FLOW IN VERTICAL TUBES



Ms. Malasri Janumporn

A Thesis Submitted in Partial Fulfillment of the Requirements  
for the Degree of Master of Science  
The Petroleum and Petrochemical College, Chulalongkorn University  
in Academic Partnership with  
The University of Michigan, The University of Oklahoma,  
and Case Western Reserve University

2001

ISBN 974-130-707-1

I 10737464

**Thesis Title:** Two-Phase Flow in Vertical Tubes  
**By:** Malasri Janumporn  
**Program:** Petrochemical Technology  
**Thesis Advisors:** Prof. James O. Wilks  
Dr. Pomthong Malakul

---

Accepted by the Petroleum and Petrochemical College, Chulalongkorn University, in partial fulfillment of the requirements for the Degree of Master of Science.

*K. Bunyakiat*  
.....College Director  
(Assoc. Prof. Kunchana Bunyakiat)

**Thesis Committee:**

*James O. Wilkes*  
.....  
(Prof. James O. Wilkes)

*Pomthong Malakul*  
.....  
(Dr. Pomthong Malakul)

*Kitipat Siemanond*  
.....  
(Dr. Kitipat Siemanond)

## บทคัดย่อ

มาลาศรี จันทร์อัมพร: การไหลของของไหลสองสถานะในท่อแนวตั้ง (Two-Phase Flow in Vertical Tubes) อ. ที่ปรึกษา: ศ. เจมส์ โอ วิลส์ และ ดร. ปมทอง มาลากุล ณ อยุธยา 79 หน้า ISBN 974-130-707-1

ท่อพลาสติกใสขนาด 0.19 เมตร x 3 เมตร (เส้นผ่านศูนย์กลางภายใน x สูง) ถูกสร้างขึ้นเพื่อทดลองการไหลแบบขนานของน้ำและอากาศ ในการศึกษา การไหลแบบพองน้ำและกระสุน ถูกสร้างโดยปรับเปลี่ยนความเร็วอากาศในช่วง 0.0029 ถึง 0.7042 เมตรต่อวินาที ส่วนความเร็วของน้ำในช่วง 0 ถึง 0.1470 เมตรต่อวินาที การไหลนี้ถูกบันทึกด้วยกล้องวีดีโอดิจิทัล นอกจากนี้ยังได้มีการศึกษาเกี่ยวกับความเร็วพุ่งขึ้นของกระสุนอากาศในน้ำ ทั้งแบบเดี่ยวและต่อเนื่อง (rise velocity of single slug and continuous slugs) อัตราส่วนว่างของอากาศ (void fraction) และการปฏิบัติการของเครื่องสูบอากาศแรงดันอากาศภายในการไหลแบบกระสุน (air-lift pump operation) ผลการทดลองทั้งหมดสอดคล้องกับผลที่ได้จากแบบจำลองของนิคกลิน (Nicklin's model) ยกเว้นผลจากการปฏิบัติการของเครื่องสูบอากาศแรงดันอากาศภายในการไหลแบบกระสุน ซึ่งผลที่ได้ยังไม่สอดคล้องกัน

## ABSTRACT

4271010063: PETROCHEMICAL TECHNOLOGY PROGRAM

Malasri Janumporn: Two-Phase Flow in Vertical Tubes.

Thesis Advisors: Prof. James O. Wilkes, and Dr. Pomthong

Malakul, 79 pp ISBN 974-130-707-1

Keywords: Two-Phase Flow/Vertical Flow/Slug Flow/Rise Velocity/Void Fraction /Air-lift Pump

A column apparatus was designed and constructed to enable that the cocurrent two-phase flow be studied in a 0.019 m x 3.0 m (inside diameter x height) vertical tube with air and water as gas and liquid phases, respectively. In this study, bubble and slug flow patterns were produced by varying the inlet air and water flow rates. The superficial gas velocities studied were in the range of 0.0029 to 0.7042 m/s, while the superficial liquid velocity was varied from 0 to 0.1470 m/s. The resulting flow types were observed and filmed with a camcorder. Once a sufficient range of inlet conditions has been observed, flow pattern maps can be created for the vertical tube systems. More importantly, this thesis also investigated relation between rise velocity of single slug and the slug length, void fraction measured by quick closing valve technique at different air and water flow rate, rise velocity of continuously generated slugs, and air-lift pump operation within slug flow. All the results agreed well with values predicted by Nicklin's models for slug flow except air-lift pump operation within slug flow where some discrepancies were observed.

## ACKNOWLEDGMENTS

This research was made possible through financial support from New Faculty Development Fund (NFDF). I thank Prof. James O. Wilkes and Dr. Pomthong Malakul, my advisors for supporting and suggestion, my friends for helping me carry out the experiments and my family for encouragement. In addition, I thank the technicians of the college for construction and repair apparatus to run experiments.

## TABLE OF CONTENTS

|                                     | <b>PAGE</b>   |
|-------------------------------------|---------------|
| Title Page                          | i             |
| Abstract (in English)               | iii           |
| Abstract (in Thai)                  | iv            |
| Acknowledgments                     | v             |
| Table of Contents                   | vi            |
| List of Tables                      | viii          |
| List of Figures                     | ix            |
| List of Symbols                     | xii           |
| <br><b>CHAPTER</b>                  |               |
| <b>I INTRODUCTION</b>               | <b>1</b>      |
| 1.1 Flow Regimes                    | 2             |
| 1.2 Bubble Flow                     | 3             |
| 1.3 Slug Flow                       | 5             |
| 1.4 Gas-Lift Pump Operation         | 7             |
| <br><b>II LITERATURE SURVEY</b>     | <br><b>9</b>  |
| <br><b>III EXPERIMENTAL</b>         | <br><b>12</b> |
| 3.1 Materials                       | 12            |
| 3.2 Equipment                       | 12            |
| 3.2.1 Design and Experiment Setup   | 12            |
| 3.3 Methodology                     | 15            |
| 3.3.1 Parameters                    | 15            |
| 3.3.2 Experiment Procedures         | 16            |
| 3.3.3 Data Calculation and Analysis | 17            |

| <b>CHAPTER</b> |  | <b>PAGE</b> |
|----------------|--|-------------|
| <b>IV</b>      | <b>RESULTS AND DISCUSSION</b>  | 19          |
|                | 4.1 Determination Flow Regimes   | 19          |
|                | 4.2 Determination Rise Velocities of Single Slug<br>( $u_b$ ) and Slug Length                | 20          |
|                | 4.3 Determination Void Fractions at a Variety of<br>Air and Water Flow Rate Within Slug Flow | 23          |
|                | 4.4 Determination Rise Velocities of Continuously<br>Generated Slugs ( $u_s$ )               | 27          |
|                | 4.5 Determination Air-Lift Pump Operation  | 31          |
|                | 4.6 Determine $u_b$ from Potential-Flow Theory   | 32          |
| <b>V</b>       | <b>CONCLUSIONS</b>   | 39          |
|                | <b>REFERENCES</b>  | 40          |
|                | <b>APPENDICES</b>  | 41          |
|                | <b>Appendix A</b> Table of experimental data   | 41          |
|                | <b>Appendix B</b> Calibration of rotameters  | 68          |
|                | <b>CURRICULUM VITAE</b>  | 79          |

**LIST OF TABLES**

| <b>TABLE</b> |  | <b>PAGE</b> |
|--------------|--|-------------|
| A1           | Determination the flow regimes   | 42          |
| A2           | Determination rise velocity of single slug ( $u_b$ ) and slug length   | 47          |
| A3           | Determination void fractions and rise velocities of continuous generated slugs at a variety of air and water flow rate | 48          |
| A4           | Error bar calculation for void fraction within slug flow   | 54          |
| A5           | Error bar calculation for rise velocities of continuous generated slugs  | 60          |
| A6           | Determination air-lift pump operation  | 66          |
| B1           | Calibration of the first air rotameter   | 69          |
| B2           | Calibration of the second air rotameter  | 74          |
| B3           | Calibration of water rotameter   | 76          |



| <b>FIGURE</b>   | <b>PAGE</b> |
|---|-------------|
| 4.7 Comparison of void fraction calculated from equation (9) with that determined experimentally with a 19 mm inside diameter tube at 500 ml/min (2.93 cm/s) water flow rate    | 24          |
| 4.8 Comparison of void fraction calculated from equation (9) with that determined experimentally with a 19 mm inside diameter tube at 1000 ml/min (5.88 cm/s) water flow rate   | 25          |
| 4.9 Comparison of void fraction calculated from equation (9) with that determined experimentally with a 19 mm inside diameter tube at 1500 ml/min (8.80 cm/s) water flow rate   | 25          |
| 4.10 Comparison of void fraction calculated from equation (9) with that determined experimentally with a 19 mm inside diameter tube at 2000 ml/min (11.74 cm/s) water flow rate | 26          |
| 4.11 Comparison of void fraction calculated from equation (9) with that determined experimentally with a 19 mm inside diameter tube at 2500 ml/min (14.70 cm/s) water flow rate | 26          |
| 4.12 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at no net water flow rate                                | 27          |
| 4.13 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 200 ml/min (1.17 cm/s) water flow rate                | 28          |

| <b>FIGURE</b>  | <b>PAGE</b> |
|--|-------------|
| 4.14 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 500 ml/min (2.93 cm/s) water flow rate   | 28          |
| 4.15 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 1000 ml/min (5.88 cm/s) water flow rate  | 29          |
| 4.16 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 1500 ml/min (8.80 cm/s) water flow rate  | 29          |
| 4.17 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 2000 ml/min (11.74 cm/s) water flow rate | 30          |
| 4.18 Comparison of rise velocity of continuously generated slugs from equation (7) with that determined experimentally at 2500 ml/min (14.70 cm/s) water flow rate | 30          |
| 4.19 Investigation of the air-lift pump operation  | 31          |
| 4.20 Gas slug in a tube  | 35          |
| B1 Calibration for the first air rotameter @ 1 bar<br>(Float: glass)   | 73          |
| B2 Calibration for the second air rotameter @ 1 bar<br>(Float: stainless steal)  | 75          |
| B3 Calibration for water rotameter (Float: stainless steal)  | 78          |

## LIST OF SYMBOLS

|                     |  |
|---------------------|--|
| A                   | Cross-section area of a tube               |
| a                   | Radius of a vertical tube                  |
| D                   | Inside diameter of a tube                  |
| G                   | Gas volumetric flow rate                   |
| g                   | Gravity acceleration                       |
| H                   | Height of liquid in the main column        |
| h, H <sub>0</sub>   | Height of liquid in the reservoir column   |
| J <sub>0</sub> ( )  | The zero-order of Bessel function          |
| J <sub>1</sub> ( )  | The first-order of Bessel function         |
| L                   | Liquid volumetric flow rate                |
| p <sub>1</sub>      | Pressure at point 1                        |
| p <sub>2</sub>      | Pressure at point 2                        |
| U <sub>b</sub>      | Rise velocity of a slug in stagnant liquid |
| $\bar{U}_l, U_{Lm}$ | Mean upwards liquid velocity               |
| U <sub>s</sub>      | Rise velocity of slugs                     |
| v <sub>g</sub>      | Velocity of the gas bubbles                |
| c                   | Constant value for equation (6)            |
| ε                   | Void fraction                              |
| ρ <sub>L</sub>      | Density of liquid                          |
| φ                   | Velocity potential function                |
| ψ                   | Stream function                            |